VIII.11 Analysis of the Hydrogen Production and Delivery Infrastructure as a Complex Adaptive System

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Contract Number: DE-FC36-05GO15034

Subcontractors:
Air Products and Chemicals, Inc., Allentown, PA
BP, Naperville, IL
Ford Motor Company, Detroit, MI
University of Michigan, Ann Arbor, MI
World Resources Institute, Washington, D.C.

Start Date: June 15, 2005
Projected End Date: May 31, 2008

Objectives

- Use agent-based modeling (ABM) to provide insights into likely infrastructure investment patterns.
- Deal with chicken-or-egg aspect of early transition.
- Provide answer to the question, "Will the private sector invest in hydrogen infrastructure?"

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section (4.5) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(E) Lack of Understanding of the Transition of a Hydrocarbon-Based Economy to a Hydrogen-Based Economy

(B) Lack of Consistent Data, Assumptions and Guidelines

(A) Lack of Prioritized List of Analyses for Appropriate and Timely Recommendations

Accomplishments

- Made preliminary cost assessment for Los Angeles, California.
- Estimated risk exposure of investors.
- Made proof-of-principle calculations with business decision model of investment incorporating risk aversion and chicken-egg relationship.
- Developed expansion path of distributed hydrogen production.
- Developed geographical information system (GIS) map platform for ABM modeling of Los Angeles.
- Derived lessons from previous technological innovations.
- Initiated development of Agent-Based Investment (ABI) model (80% complete).
- Developed conceptual link of ABI with Ford's Agent-Based Hydrogen Vehicle Owner and Fuel Retailer (AVR) model (90% complete).
- Initiated formalization of Argonne-Ford relationship under new Cooperative Research and Development Agreement (CRADA) to allow mutual access to ABI and AVR and use components of both models to create a full transition analysis tool; execution date expected in July 2006.

Introduction

The purpose of this project work is to analyze investment in hydrogen infrastructure during the early transition to a hydrogen economy using an agent-based modeling and simulation (ABMS) technique. ABMS is a micro-simulation technique that facilitates representation of heterogeneity in terms of many characteristics of the actors (agents) involved in the transition to a hydrogen infrastructure. These characteristics can include size, beliefs and preferences, expectations, goals, and location, among the most important. ABMS simplifies the modeling of learning by agents. In distinction from conventional modeling approaches currently applied to the hydrogen economy, ABMS relies on different objective functions (goals) for different agents; it also allows for different reactions to unmet expectations, different learning from the emerging economic environment, and different responses based on agent characteristics. It is easy to specify putty-clay capital (an investment in an earlier period of a simulation cannot change into another technology in a subsequent period), which is both realistic and facilitates analysis of quasi-rent changes (stranded investments). Altogether, ABMS is a well-suited vehicle to apply sophisticated economic models in an environment involving actors with widely differing characteristics and goals.

Early transition is expected to be a time of considerable uncertainty, when reasonable investors might hold widely differing expectations and could have different goals. An additional feature of early transition is the existence of a chicken-or-egg problem, in which potential investors in infrastructure want to wait for hydrogen vehicles to emerge on the market, but potential vehicle buyers want to wait until fuel is widely available. ABMS is a convenient tool for exploring these interactions via simulation, since analytical expressions for solutions to models with only modest complications are intractable.

Approach

The project began with a three-year duration, with preliminary model results due in the second year, but the project was reoriented before it began, its 1st-year budget was reduced by nearly 60 percent, and initial funding was delayed. The revised 1st-year goal of the project was to provide an answer to the question, "Will the private sector invest in hydrogen infrastructure?" and to focus on California as a likely region of early transition.

To accomplish the new 1st–year goal, the project developed a framework that focused on investments as business decisions and used that framework as a basis for preliminary assessment of profitability. In a parallel effort, efforts were begun to prepare the ABM for detailed simulations in the project's second year.

Results

Preliminary Cost Assessment and Risk Exposure

To assess the magnitude of the overall hydrogen infrastructure problem, the H2A models were used to estimate order-of-magnitude costs of completely replacing gasoline fuel supply for light duty vehicles with hydrogen, for Los Angeles, California, and the entire country, reported in Table 1. As a percent of national investment, these total costs are small, but on an annualized basis, they can still represent a sufficiently large percent of annual investments of companies the size of Ford, GM, Shell, and BP to induce risk aversion. This risk exposure was incorporated in the business decision model reported next.

TABLE 1. Total 20-Year Business Cost, 2018-2038

	Distributed Production (1500 kg/day SMR[a])	Centralized Production (380K kg/day SMR)
Los Angeles	$8.1 B	$9.1 B
California	$24.8 B	$27.7 B
United States	$203.9 B	$228.0 B

Source: Estimates based on H2A Production and Delivery Models
[a]steam methane reformer

Business Decision Model: Proof of Principles

A business decision model of investment was developed, incorporating a profit goal, risk aversion, and explicit consideration of the chicken-or-egg effect–the fact that infrastructure investors require customers but customers require infrastructure. Proof-of-principle calculations yielded investment of 25,000 units (abstract investment units) with risk neutrality and no chicken-or-egg aspect, 18,100 units with the degree of risk aversion commonly found in the economic literature, and 21,600 units when that degree of risk aversion is combined with a chicken-or-egg formulation. The model demonstrates the retarding effect of risk aversion as well as the expansionary effect of accounting for the chicken-or-egg aspect of an investment problem. This model will be used to guide the agent rules implemented in the ABMS.

Expansion Path of Distributed Hydrogen Production

Using the H2A models of distributed production, it was determined that a very small stock of hydrogen vehicles–420–would suffice to justify 1,500-kg/day facilities instead of 100-kg/day facilities, both operating at 70 percent capacity. The ABMS will focus on 1,500-kg/day facilities as the primary infrastructure technology for early transition.

GIS Mapping

A GIS map platform for Los Angeles was developed to serve as the spatial basis of the ABM. Locations of higher-income households, business districts with higher-paying employment, highways, traffic counts, and current gasoline stations have been coded. This will offer a realistic basis for simulating the early growth of hydrogen infrastructure in Los Angeles in year two of the project.

Lessons from Previous Technologies

To learn about the time required for market penetration of network and chicken-egg technologies, the adoptions of a number of important technologies of the previous century and a half were examined: telegraph, telephone, radio, automobile-gasoline station-paved highway, and television. Three of the five innovations had decades-long market penetration periods. None of the five had especially close substitutes. Finding ways to manage investment risks was important for each. Those with large, dispersed infrastructure requirements–telegraph, telephone, and automobile–all took several decades to reach 60% penetration levels. Radio and television–both chicken-or-egg technology packages–were initially expensive for their household target audiences, but their prices fell quickly, and their market penetrations were quite rapid. Government intervention or assistance varied considerably among these technologies, but was minimal in both telegraph and telephone. Table 2 summarizes findings on these technologies. Possibly of most importance to the hydrogen economy, none of these technologies had especially close substitutes. Lessons from these technologies will be used in specifying rules and characterizing market conditions for the ABMS,

Preliminary Assessment of Private Sector Participation in Early-Transition Infrastructure Investment in California

A second business decision model was developed to address the effect of risk aversion on the time path of infrastructure investment needed to support the market penetration of hydrogen vehicles assumed by the Posture Plan. The model was calibrated to Los Angeles. The initial supplier maximizes expected utility with a relative risk aversion coefficient of 1.5, building fewer stations than the profit maximizing number. Hydrogen production is distributed rather than centralized and uses 1500-kg/day installations. This determines the long-run price of hydrogen fuel. Average capacity utilization during the first four years is 35 percent, compared to long-run capacity utilization rate of 70 percent. This determines the price that must be charged for hydrogen fuel during the first 7 years (although this price is not needed for initial simulation).

Figure 1 shows the path of hydrogen vehicle sales under the benchmark scenario and compares it with sales that would achieve the Posture Plan's market penetration schedule. In this benchmark, asset protection motives act to delay adoption in the first twelve years. Less oil is saved in the early years than

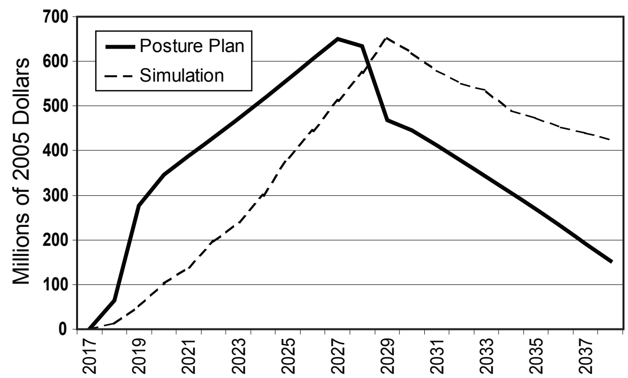

FIGURE 1. Preliminary Simulation Results of Annual Distributed Hydrogen Infrastructure Investments in Los Angeles, Posture Plan versus Simulation

TABLE 2. Lessons Learned from Previous Technological Innovations

Technology	Market Penetration		Substitutes	Initial Users	Size of Investment		Government Intervention or Assistance
	Adoption indicator	Time Required			Cost per Unit	Divisibility	
Telegraph	60% of maximum wire mileage	35 yrs	Non-electronic communication: horse, river transportation	railroads, financial industry	high	high	none of note
Telephone	in 60% of households	73 yrs	telegraph--rough substitute	businesses	moderate	high	none
Radio	in 60% of households	10 yrs	telegraph, telephone, phonograph	govt, amateurs	moderate	high	initial demand
Automobile	in 60% of households	55 yrs	horse, rail	individuals	high	high	highway construction
Television	in 60% of households	9 yrs	radio, movies	individuals	high	high	delay of commercialization, wartime R&D

under the time sequence in the Posture Plan, but the market catches up and achieves the Posture Plan goal by the twentieth year. Whether to provide government incentives aimed at speeding adoption depends on the importance of saving oil earlier rather than later. The benchmark simulation is a tentative, first illustration and will be refined in subsequent work. In the remaining years of the project the analysis will be expanded greatly and will include more attention to spatial relations, and inter-play between hydrogen fuel supply and demand for vehicles as factors affecting adoption and policy needs.

Agent-Based Model

The full Agent-Based Transition model will include two linked modules: the ABI model and an Agent-Based Hydrogen Vehicle Owner model. The investment model focuses on production and distribution infrastructure and is the locus of the most innovative work. The framework of the vehicle owner model was developed by Ford in 2004. Complete execution of a CRADA is anticipated for July 2006, which will permit incorporation of components of the Ford model with the investment model.

The ABI simulates profit-maximizing investment decisions under uncertainty by independent hydrogen infrastructure suppliers. The agent structure allows modeling of different financial characteristics, expectations, preferences (such as risk aversion), and technological constraints for different classes of potential investors. Multiple goals are permitted for each investor agent. An important component of expectations is the growth of vehicle ownership, which represents the chicken-or-egg aspect of the transition. Corresponding expectations of fuel infrastructure availability will be developed in the vehicle owner model, completing the modeling of the chicken-egg aspect of early transition. If, after investment in period t, the investing firm's expectations are not met, expectations will be revised, and the decisions for the following period will be adjusted accordingly. The firms learn over time about events that may have diffuse subjective probability distributions in early periods. Infrastructure can be retired, but physical facilities cannot be converted into another form of facility in a subsequent period.

The spatial component of the ABI relies on locations of anticipated vehicle owners. The vehicle ownership model will include sufficient characteristics of prospective vehicle owners to allow infrastructure investors to form expectations of classes of vehicle buyers, together with their residential and employment locations and the driving links between those sites. This will permit locational choices to be one of the components of investment decisions.

Conclusions and Future Directions

- Hydrogen infrastructure investments are small relative to total national investment but may be big relative to even very large companies–moms & pops won't be distributed station investors.
- Risk aversion is a relevant consideration and will have a noticeable dampening effect on infrastructure investment.
- If chicken-egg problems can be surmounted, investment would proceed more rapidly than in markets with completely independent supply & demand functions.
- Agent-based modeling necessary to address early transition's complexity and chicken-egg problems.
- Empirically specify goals, profitability & expectations components of business decision algorithms (FY 2006).
- Focus on distributed production (FY 2006).
- Initial ABM simulations (FY 2007).
- Extend analysis to additional pathways (FY 2007).
- Experiment with additional business decision algorithms (FY 2007).
- Internalize stranded asset analysis (FY 2007).
- Allow agents to have different technology (capital) access (FY 2007).
- Include option to skip annual public announcements regarding investment decisions so that information would become available as the infrastructure buildup unfolds (FY 2007).
- Include option to add probabilities to announcements to reflect announcement gaming (FY 2007).
- Allow ABI agents to accelerate, delay, or abandon investment projects as new information about demands, new capacity additions, retirements, and competitors' plans evolve (FY 2007).

FY 2006 Publications/Presentations

1. A presentation on the full scope of the project was given at the FPITT meeting (April 2006).

2. A presentation on the full scope of the project was given at the DOE Annual Merit Review Meeting (May 2006).